MANTLE PLUMES WITH TEMPERATURE-DEPENDENT VISCOSITY: IMPLICATIONS FOR INTERPRETATION OF GRAVITY ANOMALIES ON VENUS

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In recent years, two very different views about the nature and style of mantle convection on Venus have developed. In one view, convection on Venus is vigorous, with a high Rayleigh number and Earth-like heat flow [1-4]. In this model, structures such as Beta, Atla, and Eistla Regiones are the surface expression of upwelling mantle plumes. Alternatively, a rather thick lithosphere and low heat flow have been suggested [5-7]. Interpretation of Magellan short-wavelength gravity anomaly observations over shield volcanos in terms of elastic flexural support [8,9] also contributed to the thick lithosphere view, although estimates of elastic thickness have tended to decline as the resolution of the gravity field has improved [4]. An alternative interpretation of these short-wavelength gravity anomalies is that they are also the result of vigorous mantle convection. High Rayleigh number plumes have narrow thermal upwellings and numerical simulations have shown that such plumes may have large amplitude short-wavelength gravity anomalies [10]. If this style of convection occurs on Venus, there may be no need to invoke a thick lithosphere to explain the short-wavelength gravity anomalies.

Convection with Temperature-dependent Viscosity

Because of the strong contrast between these two competing views of Venus, it is important to test the proposed models under the most realistic conditions possible. One important consideration for mantle plume models is the temperature-dependence of viscosity. Because of the narrowness of high Rayleigh number mantle plumes, the viscosity may vary significantly over short distances. This is likely to be particularly important in calculating the short-wavelength components of a mantle plume's gravity and topography signatures.

Accordingly, a series of numerical simulations have been performed of cylindrical axisymmetric mantle plumes. In these calculations, the rheology is assumed to follow an Arrhenius-type law, with viscosity proportional to exp(E/RT), where E is the activation energy, R is the gas constant, and T is the absolute temperature. This form of the viscosity law is motivated by laboratory studies [e.g., 11] and is more realistic than models that assume a linearized version of the viscosity law [7]. These calculations do not include the effects of non-Newtonian rheology. However, previous calculations indicate that such effects can be approximately included by dividing the laboratory value of the activation energy by the stress exponent and using this reduced activation energy in the model calculations [12]. This approach is followed in the calculations performed here. In addition, a maximum viscosity is imposed, because at low temperatures, the strength of the lithosphere will be limited by brittle failure rather than by viscous flow.

In assessing the relevance of these models, one must consider several things. First, the long-wavelength geoid and topography from these plume models must remain consistent with observations. Second, the short-wavelength convective admittance must be large if this model is to be a suitable alternative to the thick elastic lithosphere model. Third, the short-wavelength convective gravity anomaly must be a significant fraction of the observed short-wavelength anomalies: the amplitude of the convective admittance is of little relevance if convection contributes only a small fraction of the total short-wavelength signal. Initial results [10] indicate that temperature-dependent viscosity significantly enhances both the short-wavelength gravity anomaly and the admittance relative to comparable models that include only depth-dependent viscosity. The admittance result is consistent with the findings of other investigators [13]. These results are currently being extended to a broader range of Rayleigh numbers and rheological parameters. The implications of these models for the interior structure of Venus will be assessed by comparing model gravity anomalies with the gravity field derived from Magellan observations, recently completed to spherical harmonic degree 120 [14].

Time-dependent Mantle Convection

There are two different types of time-dependent behavior of mantle plumes that one can consider. One type of time-dependence involves the initial ascent of a mantle plume towards the surface of Venus. The time-dependent behavior of the geoid and topography in this case has been well studied [15]. The second type of time-dependence involves a preexisting mantle plume, with boundary layer instabilities causing time-dependent changes in the plume's thermal structure and hence in the geoid and topography produced by the plume [16]. Including temperature-dependent rheology in a mantle convection calculation strongly increases the tendency for the model to exhibit time-dependent behavior. In isoviscous, aspect ratio one mantle plumes, steady-state thermal structures exist up to a Nusselt number (a measure of convective vigor) of at least 21 [17]. When an Arrhenius temperature-dependent rheology is included, aspect ratio one plumes become time-dependent at a Nusselt number between 8 and 11. A number of volcanic highlands on Venus with a variety of gravity and topography signatures have been proposed to be mantle plume related [1,9,18]. If high Rayleigh number mantle convection does occur on Venus, it is almost certainly time-dependent due to the development of thermal boundary layer instabilities. The fluctuations in convective gravity and topography produced by these boundary layer instabilities may contribute to the regional variations in gravity and topography among the various Venus hotspot swells.

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